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Current heavy-fuel military tactical generator sets in the 10 to 15 kw class use Diesel engines which drive low speed (3600 rpm) electrical generators. These gen sets have weight-to-power ratios that range from about 100 to 150 lbs/kw and volume-to-power ratios from about 4.0 to 5.3 ft3 per kw.

In this program a preliminary design was completed for a 15 kw class dual-use, compact, light-weight portable turboelectric power gen system (designated the LTS22) with efficiency equal to the best current Army generators, a weight of approximately 100 lb (weight-to-power ratio of less than 7 lb/kw) and a volume of approximately 6.2 cubic feet (volume-to-power ratio of 0.4 ft3/kw) Thus the weight and size of the LTS22 turboelectric gen set would be approximately 1/10 of today's US Army gen sets.

The LTS22 generator preliminary design uses a high speed microturbine engine with an integral permanent magnet generator and electronic power controller to achieve a very light weight system. A high effectiveness, compact laminar flow (CLF) recuperator together with a low pressure-ratio turbine cycle will achieve an overall system efficiency equal to the current small diesel powered gen sets.

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Enclosure 1

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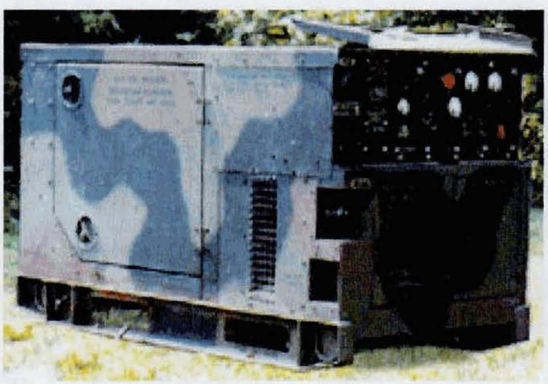
Problem Statement:

Locust USA, Inc. was funded by DARPA through an Army ARO contract to conduct conceptual design studies to define a 15 KW class gas turbine powered, small portable turboelectric power generation system. Also, this program included completing a preliminary design of the most attractive concept including preliminary layouts of all components and the integration of these components into a system package cabinet.

Current technology military tactical generator sets in the 10 KW to 15 KW class use heavy fuel Diesel engines and low speed (3600 rpm) generators. These generator sets have weight to power ratios that range from about 100 to 150 lbs./KW and have volume to power ratios that range from about 4.0 to 5.3 ft^3/KW. Two examples of these generator sets are the Army Quiet Tactical Generator (QTG) sets shown in Figure 1. As can be seen, these Diesel generators are very heavy, occupy large volumes, and therefore, impose challenges on the existing Military Logistics system.



Model:	MEP 803A	MEP 804A
Power:	10KW	15KW
Weight:	1182 lbs	2124 lbs
Volume:	41 ft^3	77 ft^3

Figure 1. Army Quiet Tactical Generator Sets

However, these generators do have high electrical efficiencies (power output divided by fuel input power) or system efficiencies that can reach 25% or slightly higher. At part power operation, electrical efficiencies are considerably lower due primary to Diesel throttling loses at constant speed.

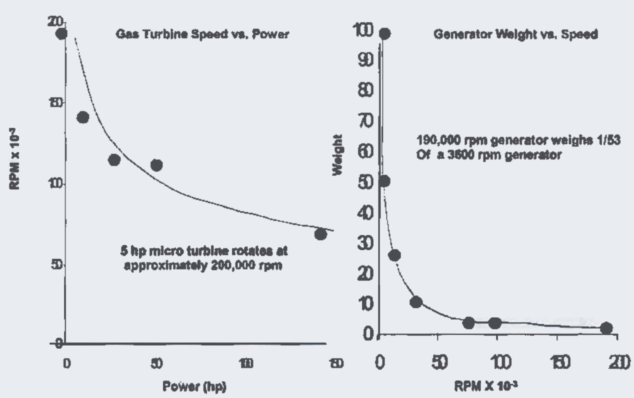
Summary of Results

Design Summary and System Performance

In the power range from 30 KW to about 200 KW a number of turbine driven generators have been developed or are in development for the commercial market. The most successful has been the 30 KW Capstone C30. The C30 is a stationary non-mobile system that has a weight to power ratio of 44 lb/KW and volume to power ratio of 2.8 ft^3/KW, which shows the potential of turboelectric generators in this size class. Below the 30 KW size there have not been any successful turboelectric systems developed.

Locust has a number of heavy fuel turbine engines under development between 5 h.p. and 40 h.p. that include both simple cycle (no recuperator) and recuperated cycle designs. The recuperator is a heat exchanger that transfers waste exhaust heat to the compressor discharge air before it enters the combustor. This reclaimed heat reduces the amount of fuel that is burned in the combustor with a resulting large improvement in brake specific fuel consumption (BSFC) and thermal efficiency. The Locust simple cycle engines (without gearboxes or generators) in this power range have weight to power ratios that range from about 0.45 to 0.59 lbs/h.p. and the recuperated cycle engines range from about 0.88 to 1.9 lbs/h.p. Typical small diesel engines in this power range weigh about 10 to 15 lbs./h.p, A comparison of these weight to power ratios shows the large weight savings potential that can be obtained with turbine powered generators. A further even larger weight and volume savings can be obtained by integrating a high-speed permanent magnet generator directly on the turbine engine rotor shaft between the bearings.

Figure 2 Turbine Driven Generators Are Very Light Weight



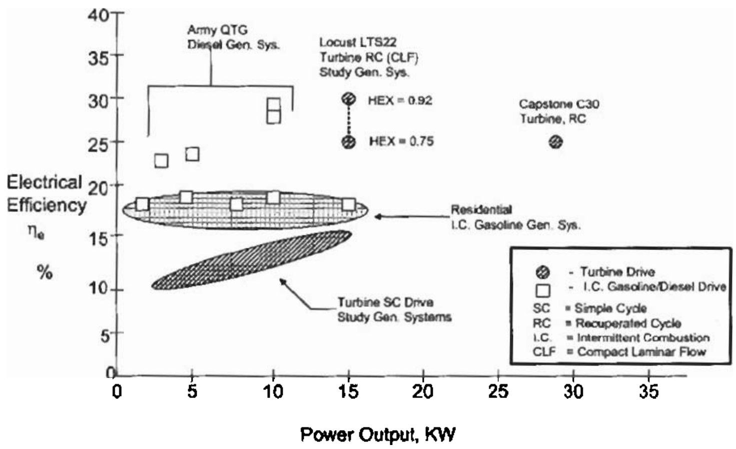
Small size turbine engines operate with very high shaft rotational speeds as shown in Figure 2. At power levels near 5 h.p. turbine speeds are approaching 200,000 rpm. This high speed turbine can be designed to incorporate an integral high speed generator rotor on the engine shaft or a low speed generator (3,600 rpm) can be driven from a gearbox through a coupling. As shown the high-speed permanent magnet generator will weigh only about 2% of the low speed (3,600 rpm) generator. This occurs as the basic power equation for electric machines have weight proportional to power divided by generator speed as shown below.

$$P = kD^2L \times N, \qquad D^2L \;\alpha\; W \;\alpha\; P/\,kN$$

The weight trend shown in Figure 2 was done for the Locust LTS5 EXO 2KW generator. As speed is increased from 3,600 rpm to the engines 190,000 rpm, generator weight is reduced by a factor of 53X. For the 15 KW class generator where turbine speed is near 121,300 rpm weight is reduced by a factor of about 34X relative to a 3,600 rpm generator. If an average Diesel power to weight ratio of 12.5 lb/h.p. is used, the 15 KW class recuperated turbine engine with an integral high speed generator will weigh less than the Diesel with a 3,600 rpm generator by a factor of from 224X to 482X.

Recuperated cycle turbines offer the potential of much higher thermal efficiencies (lower BSFC's) than the lighter simple cycle turbines. When the recuperated cycle turbine is combined with very efficient high-speed permanent magnet generators and electronic power converters an overall electrical efficiency similar to the Army QTG generators can be obtained (Figure 3) at a much lighter system weight and volume.

Figure 3 Comparison of Low Speed Intermittent Combustion and High Speed Turbine Generator System Efficiency



The overall objective of the Locust LTS22 Small Turboelectric Power Generation System program was to develop a preliminary design of a 15 KW class dual use, light weight, portable generator as shown in Figure 4. Potential applications include Army ground power and aviation mobile power, and residential/industrial emergency power.

Figure 4 LTS22 Small Turboelectric Power Generation System Objective

Objective

- Design 15 KW Class Dual Use Compact Light Weight Portable Turboelectric Power Generation system for:
  - Army Ground Power
  - Army Aviation Mobile Power
  - Dual Use Potential
    - Residential/Industrial Emerg. Power

As part of the LTS22 program power rating requirements were developed for the three potential user applications (Figure 5). At sea level standard day conditions required power was 15.0 KW and at the 4,000 ft high temperature condition of 120 F the power requirements was established as 10.7 KW. The types of output power required were: 28 VDC, single phase 120 VAC and 240 VAC, and three phase 208 VAC.

Figure 5 LTS22 Applications & Power Ratings

Application	Altitude	Ambient Temperature	Turbine Inlet Temperature	Power Outlet
Army Ground Power	4,000 ft.	120 F	1800 F	10.7KW
Army Aviation Mobile Power	Sea Level	59 F	1700 F	15.0KW
Dual Use Potential – Residential/Industrial Emergency Power	Sea Level	59 F	1700 F	15.0KW

The key features and overall performance of the Locust LTS22 generator are shown in Figure 6 along with a Pro-E solid model. This preliminary design incorporates a single shaft one-piece rotor with back-to-back centrifugal

compressor and radial inflow turbine as shown in Figure 7. The compressor has a design pressure ration of 4.0 and sea level standard day airflow of 0.333 lb/sec. Cycle studies showed that the minimum BSFC of 0.498 occurred at this pressure ratio for a recuperated engine with a heat exchanger effectiveness of 75.3%. Engine speed is 121,300 rpm at this condition and 130,500 rpm at 4,000 ft. and a 120 F day. To minimize engine size and weight, a compact laminar flow (CLF) recuperator is incorporated. Compressor discharge air enters the recuperator near the outer diameter and flows rearward and radially inward. The hot exhaust flows radially from the inner diameter to the outer diameter. With this design, the hot section (turbine, combustor and recuperator) is separated from the forward cold bearing compartment. A high-speed permanent magnet generator rotor is integrated between the rotor shaft bearings as shown in Figure 7. The bearing inner rings are mounted directly on the generator rotor to enhance rotor system dynamics at the high rotational speed. The LTS22 is 14.88 inches in length with a diameter of 9.90 inches. An annular inlet is located around the perimeter of the generator stator. Inlet air is used to cool the generator, bearings and AC to DC electronic starter rectifier, which wraps around the outside of the inlet. The electronic power converter also includes a synchronous rectifier/inverter and inverter, which are located next to the LTS22 engine. These inverters are cooled by a separate integral electric cooling fan. At the full 15 KW rated power condition electrical efficiency is estimated to be 24.6%. If a larger recuperator with an effectiveness of 92% is substituted for the baseline 75.3% design, electrical efficiency would increase to 30.1% , however, engine weight would increase. When all of the LTS22 generator components are integrated into a system package cabinet the overall weight is estimated to be about 100 lbs. and volume is about 6.2 ft^3.

Figure 6 LTS22 Turboelectric Generator Key Features & Performance

Key Features

•Single shaft/one piece rotor

•CLF Recuperator

•Integral High Speed Generator

•Separate Cold/Hot Sections

•Electronic Power Converter

Performance

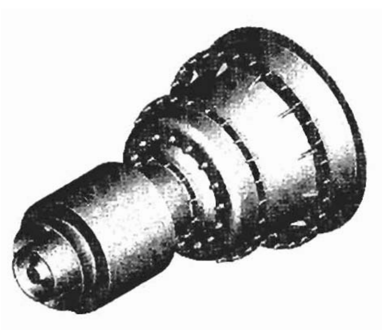
•Power Output – 15 KW

•Engine BSFC – 0.498

•Speed – 121,300 rpm

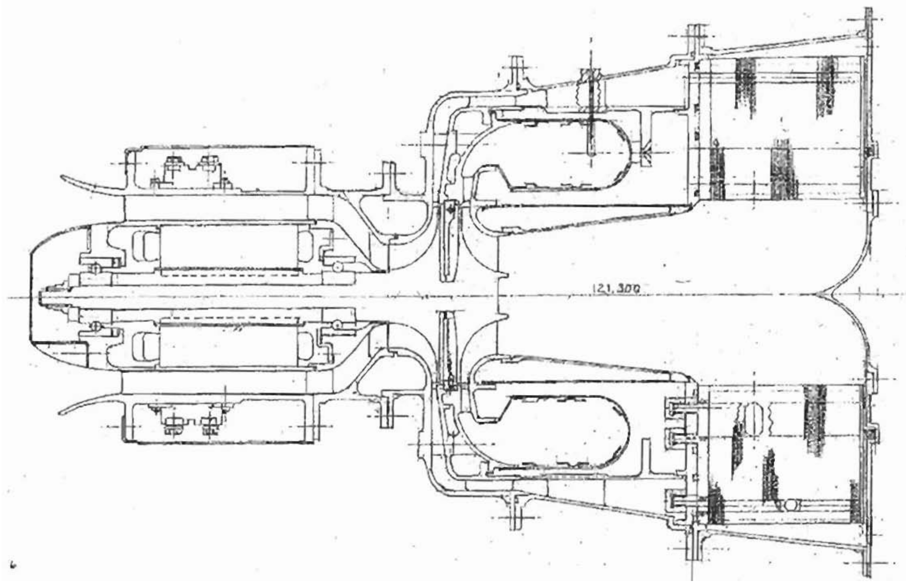
•Electrical Efficiency – 24.6%

•System Weight ~ *100 lbs.



*For Output power types: 28vdc, single phase 120v & 240v, and three phase 208v

Figure 7 LTS22 Cross Section



Compressor

A preliminary design has been completed for a 4 pressure ratio, 0.33 lb/sec centrifugal compressor for the LTS22 engine. This design is based on another gas turbine engine under development at Locust with a slightly higher pressure ratio called the baseline. The flow path is shown in Figure 8 the design parameters are given in the Table 1. The design is strongly influenced by the flow, pressure rise and efficiency achieved in the baseline engine.

The physical RPM is set so that both the turbine and compressor operate at aerodynamic loading levels consistent with good efficiency and lightweight. Work coefficients (thermodynamic work normalized by tip speed) are quite consistent between the two Locust designs. Tip speed is reduced in the LTS22 because of the lower pressure ratio. The lower pressure ratio allowed a modest increase in specific speed which is a benefit to efficiency. Low specific speed is detrimental to efficiency because the flow path of a low specific speed compressor has more wetted area and hence more viscous drag.

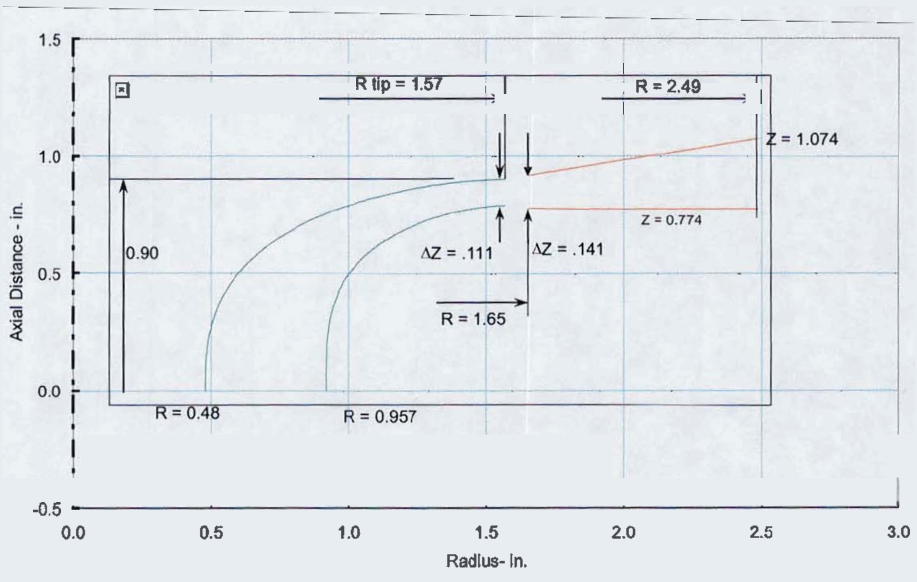
The effects of pressure ratio, size (Reynolds number, edge thickness, roughness and clearance), specific speed and Mach number are all taken into account in determining the projected efficiency levels. The net effect of the smaller size and lower pressure ratio is a small, 0.3% decrement relative to a base compressor with which Locust has experience.

The static pressure rise and hence the area ratio of the diffuser is reduced somewhat from the baseline Locust compressor because of the lower pressure ratio. The divergence angle and number of channels is held constant. The projected pressure rise is consistent with data from the baseline compressor and a large body of published diffuser data.

Table 1 LTS22 Compressor Preliminary Design Summary

		LTS22
Performance		
Pr		4.000
Flow	lb/sec	0.333
η		77.4%
RPM		121,300

Figure 8 LTS22 Compressor Flowpath



Turbine

The LTS22 turbine component uses a single radial stage which provides the power to drive the engine's single stage centrifugal compressor and also to drive the electrical generator, both of which are directly on the same rotor shaft. The turbine develops a total mechanical power of approximately 60 horsepower from the mainstream flow. Fifty-eight percent of that power is required to drive the engine compressor (including mechanical losses in the bearings, windage losses, etc.) while forty-two percent (25.3 hp) is used to drive the electrical generator to produce electric power output.

A turbine meanline design analysis was used to define the required flowpath geometry, number of airfoils, turbine efficiency and other basis aerodynamic parameters. The preliminary flowpath geometry is shown in Figure 9. The turbine design uses 26 stator vanes and 14 rotor blades. The total-to-total pressure ratio of the turbine is 3.53, which easily can be accommodated in a single radial stage. The work level is a reasonable 136 Btu/lb. The velocity ratio, which reflects the ratio of turbine wheel speed to the square root of the turbine work, is 0.60, a value that is comfortably high. This velocity ratio indicates that a major portion of the turbine work will be achieved by wheel speed, requiring a reasonable level of gas turning. This favorable level of velocity ratio (sometimes called work coefficient) makes possible an excellent level of turbine efficiency. The predicted level of total-to-total efficiency is 84.5%. The static pressure reaction level is 46% which is considered to be near optimal. Other aerodynamic parameters of interest include a stator vane inlet Mach number of only 0.103 and an exit Mach number of 0.880. The rotor blade inlet relative Mn is 0.292 and the exit absolute Mn is 0.379. Flow exits the turbine rotor with an average swirl angle of 36.5 degrees.

Figure 9 below shows the turbine flowpath dimensions. The shroud contours shown are approximate and the drawing is not to scale.

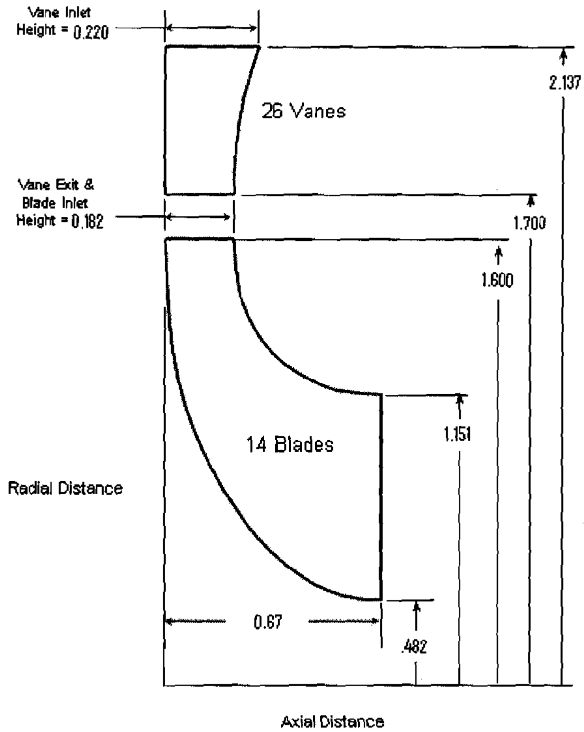


Figure 9. LTS22 Single Stage Radial Turbine Flowpath Elevation

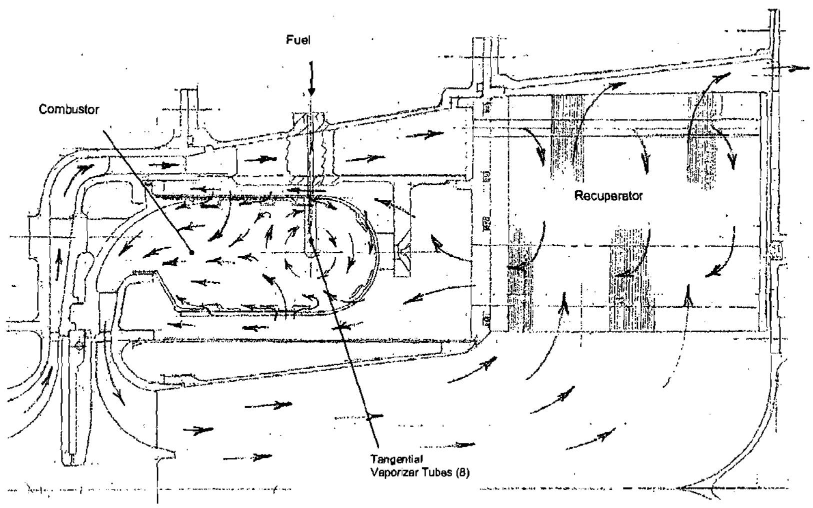
The combustor exit temperature of 1700F (2160R) was selected to allow long life in the turbine without requiring turbine cooling. With a 1700F temperature out of the combustor, the turbine rotor blade average relative temperature is only 1456F (1916R) at the inlet and 1315F (1775R) at the blade exit plane. These temperatures are sufficiently low to avoid creep/stress-rupture in the advanced high-temperature nickel base alloys used for the LTS22 turbine. Also, the stator vane life (limited by local oxidation/erosion due to hot-spots) will be long because in the highly recuperated LTS22 engine the combustor temperature rise is relatively small (approximately 700F), which will result in a uniform temperature into the turbine.

Combustor

The conceptual design of the LTS22 combustor was formulated to meet the unique requirements of a recuperated-cycle, which include high-range inlet air temperatures and a low temperature rise rating compared to equivalent simple-cycle combustors. An annular configuration was selected that will allow close-coupling of the combustor to an annular recuperator, so that the combined size and weight of these hot section components can be minimized. Annular passages are provided to conduct airflow from the compressor to the recuperator and then back to the combustor. Hot gases exiting the combustor travel radially

inward through the turbine and then radially outward through hot-side channels in the recuperator.

Figure 10 LTS22 Combustor and Recuperator



The LTS22 annular combustor (Figure 10) is a reverse-flow design based on Locust small-engine design practice that incorporates unique design features for injecting and igniting heavy fuel. Locust has developed a successful design system for small-engine combustors ranging in size from 5 HP class to 150 HP class. It has been validated by compiling extensive rig test data on designs of 150 HP, 60 HP, and 5 HP engine size class, and in subsequent engine testing. The design methodology encompasses basic sizing, flameholding mechanisms, stability, blowout limits, temperature pattern factor, and techniques for fuel distribution, vaporization and injection. The LTS22 combustor is scaled from the 60 h.p. larger size Locust combustor and it meets all applicable design system criteria. The combustor liner is of sheet metal construction and employs louver cooling of the annular combustion section and the combustor-to-turbine transition duct. The internal aerodynamic design accomplishes flameholding by means of a toroidal recirculating flow pattern in the dome of the combustor. Directed airflow from cooling louvers and penetration jets is used to establish the toroidal flow pattern.

Fuel is introduced tangentially into the toroidal flowfield through 8 fuel vaporizer tubes. The vaporizer tube design is based on proprietary design practice from other Locust small engines. Within each tube, fuel is injected along the inner wall where it is vaporized and premixed with air. Combustor design features and performance criteria are summarized in Table 2.

Table 2 LTS22 COMBUSTOR DESIGN FEATURES AND PERFORMANCE CRITERIA	
Type Combustor	Annular, Reverse Flow, with Convective Liner Cooling
Length (combustion annulus)	2.25 in.
Length (overall)	2.83 in. (including transition section to turbine inlet)
Outer Diameter	5.88 in.
Inner Diameter	3.40 in.
Fuel Type	JP8
Fuel Injector Type (Initial Configuration)	Vaporizer tube

Table 2. LTS22 Combustor Design Summary

Two separate start nozzles, with integral igniters, are provided for initial lightoff. Main fuel flow to the vaporizer tubes is delayed until a stable flame is established using the start nozzles. To function successfully, the start nozzles must ignite the heavy fuel passing through them, and maintain stable flames of sufficient magnitude to heat adjacent vaporizer tubes, and rapidly ignite the main fuel. Start nozzles make it possible to propagate flame to all 8 vaporizer tubes before they are self-sustaining.

A unique start-nozzle design, developed for a small Locust engine, was rig-tested in a combustor having vaporizer tubes similar to those selected for the LTS22. The test demonstrated reliable, rapid ignition and propagation of flame to all vaporizer tubes. Figure 11 shows a typical lightoff sequence.

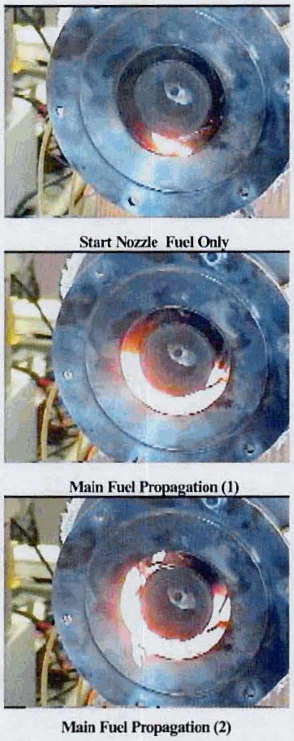
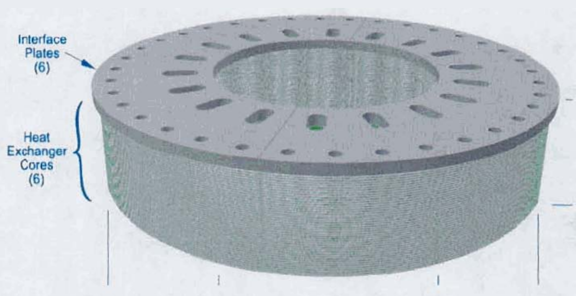


Figure 11 Combustor Rig Lightoff Test

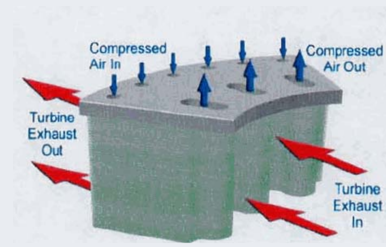
Recuperator

The LTS22 recuperator is a compact annular heat exchanger that recovers waste heat from the engine exhaust stream and transfers it to the compressor discharge air before it enters the combustor. The temperature rise achieved in this manner contributes directly to the engine-cycle temperature rise and produces a direct fuel savings. The proportion of fuel saved equals the proportion of the total temperature rise gained from waste heat. As a result of the fuel savings, cycle efficiency is improved by the same ratio.

The recuperator configuration is a counter flow arrangement of parallel-plates that have radially directed flow passages. Exhaust gases flow radially outward, while compressor air, which enters through a ring of holes near the outer radius, flows radially inward and exits through another ring of holes near the inner radius. The annular core, shown in Figures 12, is assembled from six sectors or modules, each of which contains 118 plates.



(a) Complete Recuperator Core



(b) Single Module

Figure 12 LTS22 Recuperator Concept

The dimples in each plate are brazed to the adjacent heat exchanger disk and therefore also provide internal structure to support the plates against pressure of the compressed air during operation. Dimpled foil technology enables construction of a compact heat exchanger array comprising highly uniform, closely spaced channels. Laminar flow in these channels provides the maximum heat transfer per unit pressure drop and will enable high thermal effectiveness in a compact core.

Compact, laminar flow (CLF) recuperators accomplish heat transfer using laminar flow through microchannels between parallel plates. Recent advances in fabrication technology have enabled the construction of CLF recuperators which are much more compact than older, turbulent flow plate-fin recuperators. With CLF technology, it is now possible to design high-performance recuperators that are small enough for use in small turboelectric generators.

The preliminary design of the LTS22 recuperator was conducted by scaling a slightly larger-size recuperator from the LTS40, an engine that will be tested later this year. The two engines are the same basic design and differ primarily in power output. The LTS40 recuperator detailed design was scaled to provide the same flow characteristics (manifold and channel pressure losses and Mach numbers), and heat transfer characteristics (plate area per unit flow) in the LTS22. Key design parameters for LTS22 recuperator are listed in Table 3.

Table 3. LTS22 Recuperator Design Summary

LTS22 Recuperator (Scaled Design)

		Air	Exh
Flow Rate	lbm/sec	0.313	0.316
Tinlet	R	854	1680
Pinlet	psia	58.78	15.79
Allowable ΔP/P	%	1.85	2.30
Thermal Effect.	-	0.75	

All other aspects of the design, including plate thickness and spacing, mechanical arrangement, and mounting provisions, were adopted without change. By applying these criteria, the required inner and outer diameters and length of the LTS22 recuperator were determined, and the thermal effectiveness (75.3%) of the baseline design was maintained.

With reference to Figure 10, the recuperator will function as follows. Under nominal design conditions, compressed air at roughly 4 atm pressure enters a set of manifold passages around the perimeter of the interface plates. The manifold distributes the air across 59 enclosed flow channels, through which the air flows radially inwards while absorbing heat from the hot exhaust and reaching an exit temperature greater than 1000 F. The heated air then enters the exit manifold passages and leaves the heat exchanger through the array of elongated holes near the inner diameter and enters the combustor. Hot turbine exhaust enters the heat exchanger through the central passage, flows radially outwards while transferring heat to the compressed air, and exits the heat exchanger from its outer diameter.

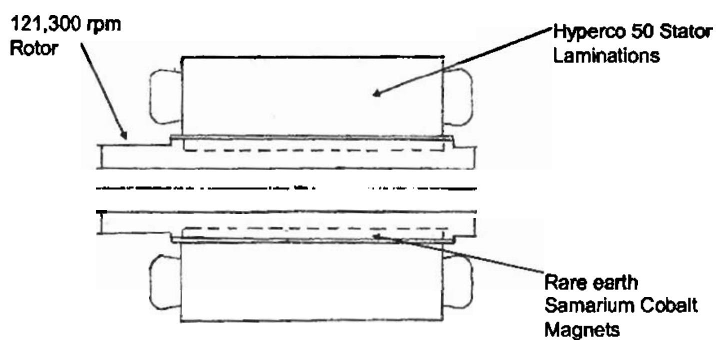
The annular heat exchanger core will be built from sheet metal plates that are produced using a precision forming/blanking process. The stack is vacuum brazed to create structural bonds and sealed joints. The core comprises an array of enclosed flow channels for the high pressure (air) stream. Uniform channels are ensured by forming precise dimples in each plate that provide very uniform spacing. These dimples are brazed to the adjacent heat exchanger plate and therefore also provide internal structure to support the plates against pressure of the compressed air during operation. The array of enclosed air channels is connected in parallel by an array of manifold passages that run the length of the heat exchanger along the inner and outer diameters. The manifold passages are created by embossments in each plate. When the plates are stacked, the embossments in one plate contact the embossments in the next plate to create a seal around the manifold passage. These manifolds enable the air flow to enter and exit the recuperator. Each manifold channel is also sealed from the exhaust flow by a mating set of flanges on the inner and outer diameter of each plate.

Generator

The LTS22 generator design uses a 4 pole, surface mounted permanent magnet rotor with a pre-stressed magnet retention sleeve fitted over the magnets to prevent lift-off during full speed operation. The rotor will be precision balanced so the retainment system maintains the integrity of the original balancing and prevents magnet pieces from coming loose during the life of the unit. The magnets are made from 2-7 samarium cobalt rated for 350 deg C and they are highly resistance to corrosion.

The stator design is based upon 6 slots with two coils per phase wound at 180 degrees apart. This is a very efficient design with 1/2 slot per pole per phase that results in very short phase winding end turns in order to keep the length of the unit as short as possible. This is because the phase coils are placed around a single stator tooth. The stator Hyperco 50 lamination stack and windings will be encapsulated in a high thermal conductive epoxy to assist in removal the of internal heat from the lamination losses and copper losses. An axial cross section of the machine is shown in Figure 13.

Figure 13 LTS22 Integral Starter/Generator



- Integral Starting & Generating Capability
- Generator Power = 15 KW
- Generator Efficiency = 97.1%
- Weight of Rotor/Stator = 2.51 lbs.

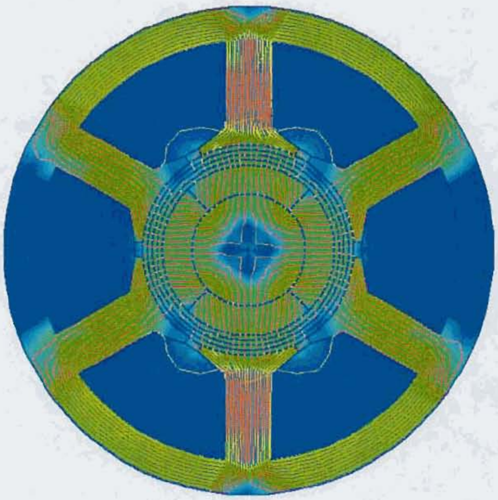
The stator lamination diameter is 2.5" and the length is 2.40". The winding end turns extend the overall stator slightly. The rotor diameter is 1.030" diameter over the retainment sleeve. The rotor is about the same length as the stator. The rotor requires precision balancing and testing at 10% over speed for rotor integrity compliance.

The phase windings consist of two coils per phase connected in parallel with 7 turns per coil. The two circuits through the machine would have separate neutral

connections and are insulated from each other to prevent any circulating stray currents that might be caused by unbalanced phases. All insulation materials used would be rated for 200 deg C minimum.

Figure 14 shows a transverse cross-section through the generator rotor showing the generator magnetic flux pattern.

Figure 14 LTS22 Generator Magnetic Flux Pattern.



The design output electrical power is 16.5 KW (22HP) producing 142 volts AC or 194VDC rectified. The phase current required is 68 Arms. The efficiency is about 97% with zero windage losses and the driving torque required by the turbine engine is approximately 0.95 Lb-Ft @ 121,300 rpm.

This generator design has very high power density due to the 4-pole design, the material used and forced convective cooling. The weight of the rotor and stator is about 2.51 lbs.

Power Converter

The purpose of the electronic power converter is to efficiently convert the unregulated generator output to an output that is suitable for powering a wide variety of loads. Two key Figures in the specification are the overload capability and the percentage of waveform distortion. For a small generator, with or without an electronic power converter, a 200% overload capability with a 3% distortion Figure is usually regarded as a reasonable expectation and is adequate for most situations.

High efficiency, low weight and minimum space requirements are usually met by minimizing the number of steps in the power conversion process and by minimizing the need for energy storage components. Of all of the possible methods that can be proposed, the arrangement of Figure 15 is the recommended concept for the LTS22. This has an input rectification stage (AC to DC conversion), an inverter stage (DC to AC conversion) and a filter stage.

An additional requirement is the provision of a 28V output of some capability for battery charging, etc. There are many readily-available, commercial, off-the-shelf components that will achieve this function very efficiently in a small space and will be used in this design. Typically, these are available in modules of up to 600W capability and can be paralleled to achieve higher power levels. These components may be powered from the AC output but greater efficiency is obtained if they are powered from the rectifier output.

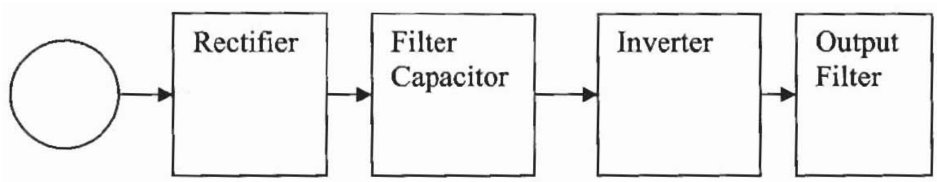


Figure 15 Two-stage Conversion Process with Unregulated Inverter Input

Rectifier

A rectifier converts the input from two Y-connected windings of a permanent-magnet generator to a center-tapped DC supply. A typical arrangement is shown in Figure 16 using fast recovery diode modules.

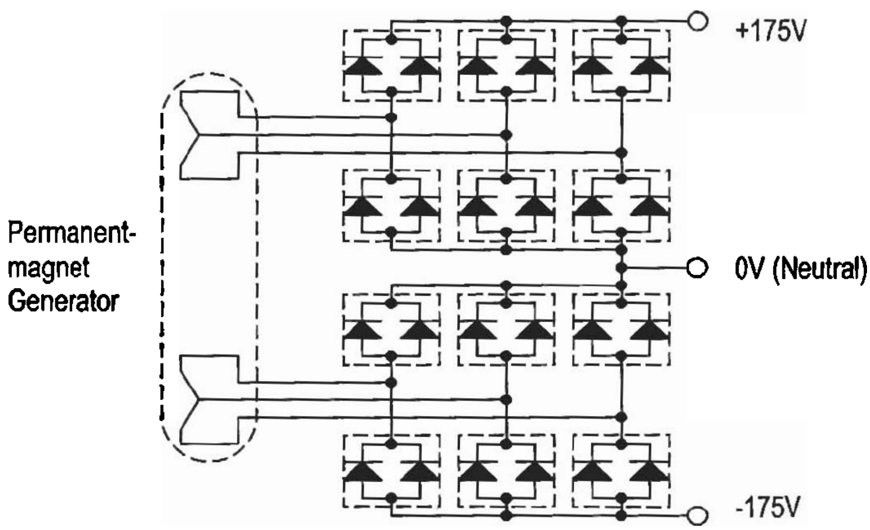


Figure 16 Rectifier Arrangement for Dual Stator Winding

Table 4: Typical Generator and Rectifier Characteristics

	Unit	Min	Typ	Max
Generator speed	krpm	115	130	145
Generator winding voltage (line/line)	Vrms	115	130	145
Generator output current (6 wires)	Arms	-	40	43.5
DC output voltage	Vdc	155	175	205
DC output current (+175V, -175V or neutral)	A	-	43	47
Full-load losses	W	260	280	300

The design of the permanent-magnet generator is adapted to the design of the rectifier in the following ways:

- The stator winding is divided into two separate wye-connected windings. Both of these windings are identical and may be created by either two parallel conductors in all of the stator coils or by two sets of equal stator coils. It is not necessary for the phase of the output voltages to match.
- The output voltage of each winding is chosen so that its rectified output is at least 175V under most operating conditions. This voltage is equivalent to the peak of a sinusoidal 120V rms output. The inverter requires a minimum input of 175V to ensure that it can deliver a distortion-free sinewave to the load.

Although it might seem desirable to design the generator winding to produce a generously-high output voltage so that the 175V minimum can always be assured, the availability of power semiconductors should be considered. Low-cost, compact, high-performance IGBT moduless are available in voltage ratings of 600V, 1200V and 1700V with almost no intermediate choices. The 600V modules are highly desirable for the inverter owing to their very low losses when operated at the high switching frequency that is necessary for minimum-size filter components. The 600V modules can be safely operated at up to 450V. This means that the output of each rectifier must not exceed 225V. A higher output voltage would require the choice of 1200V modules. The losses would be approximately doubled and would require the use of larger semiconductors and larger heatsinks.

Table 4 shows examples of typical operating conditions at speeds in the range 115,000 rpm to 133,000 rpm. The minimum speed condition shows the result of drawing the rated current at this speed. Although the output voltage is less than 175V, the inverter can still deliver adequate power but with a distorted waveform. Effectively, the peak of the sinewave is flattened by 20V. Since the turbine output capability diminishes at low speed, this cannot be regarded as a continuous operating condition. If the generator winding is assumed to have an impedance of between 10% and 15%, the voltage, the part-load conditions will result in a higher rectifier output voltage. At lesser load of around 30%, the

reduced voltage drop in the generator winding restores the rectified output to the required value of 175V. The estimated rectifier efficiency is 98.13%.

DC Bus Filter

A DC bus capacitor filters the output of the rectifier and also provides a low-impedance source for the inverter. Electrolytic capacitors will be used for this function. The power flow in a single-phase AC circuit is always pulsating at twice the supply frequency, therefore, the DC bus filter must store sufficient energy to make up the difference between the steady power flow from the rectifier and the pulsating delivery to the load.

Inverter

The inverter is constructed from two six-pack IGBT modules (Figure 17). Each pair of IGBTs in the six-pack is capable of delivering 25A continuous to its output when switched at 15kHz. It is possible to deliver 50A for brief periods for the purpose of handling surges during motor starting (Table 5). The IGBTs switch the output terminal to either the +175V bus or the –175V bus. The duty cycle during the switching period is sinusoidally modulated so as to create a fundamental component of the required amplitude and frequency with as few harmonics as possible. The output is unsuitable for many loads owing to the large component of switching frequency.

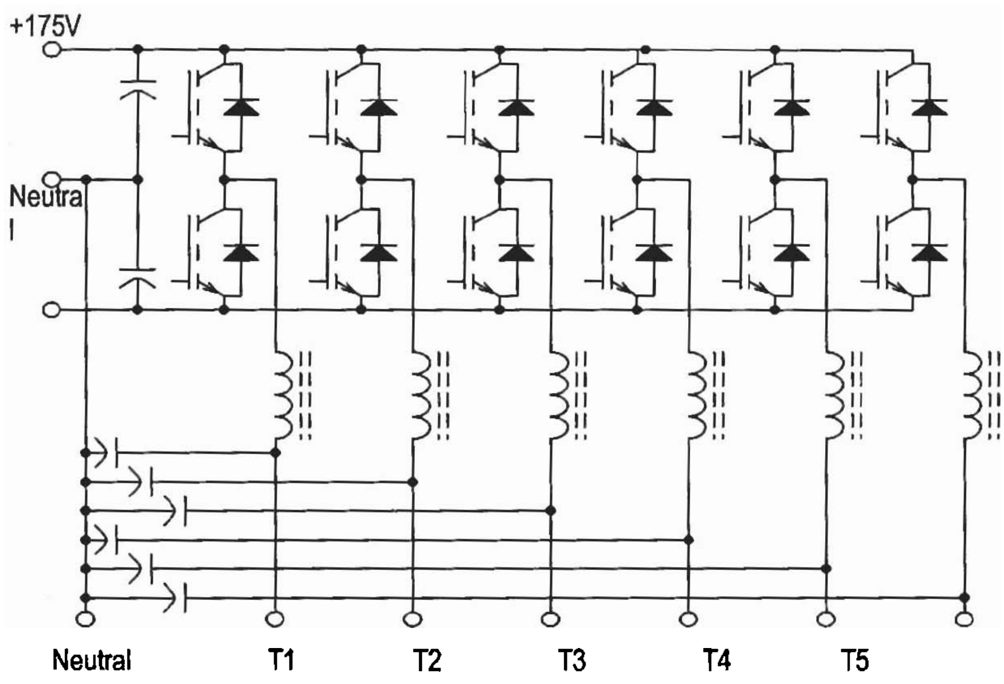


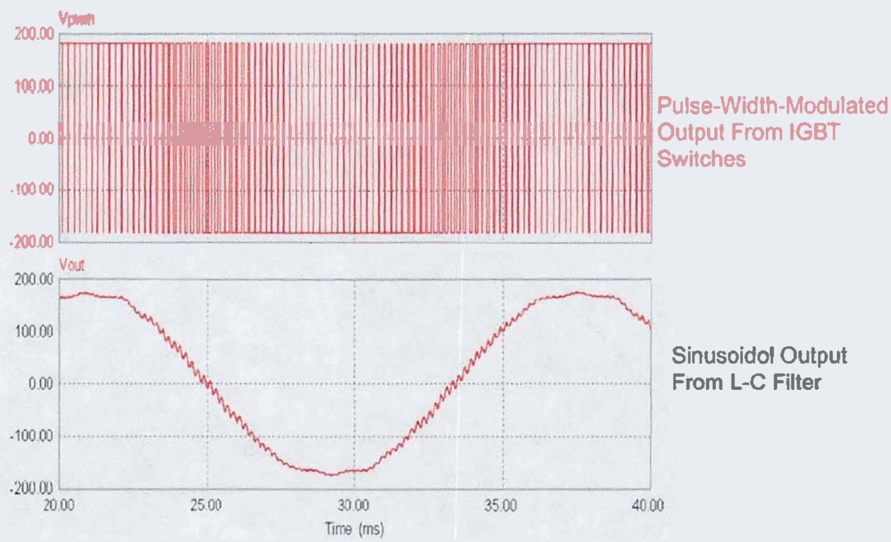
Figure 17 DC Bus Filter, Inverter and Output

Each section is followed by an L-C filter. The effect of the filter is illustrated by Figure 18. The filter reduces the switching frequency component to a very low value and leaves the desired power frequency component almost unaffected. The resulting output waveform from the filter is a close match to clean utility power.

Table 5 Inverter Performance Summary

	Unit	Min	Typ	Max
Input voltage (+ or – DC to neutral)	V	155	175	205
Input current (+ or – DC)	A	-	43	47
Output voltage (terminal to neutral)	Vrms	110	115	120
Output current (per terminal continuous at 0.87 power factor)	Arms		-	25
Output current (peak at 0.43 power factor)	Arms	-	-	50
Output power (per terminal)	W	-	-	2500
Full-load losses (all 6 terminals at 25A output current)	W	600	650	700
Harmonic distortion	-	-	1%	4%
Operating temperature (ambient air)	°C	-40	25	50

Figure 18 Effects of Output Filter



Configurations

The outputs from the six sections is designed to produce the following power configurations:

- 120V 2-wire 150A continuous, 300A peak
- 240V 2-wire 75A continuous, 150A peak
- 120V/240V 3-wire 75A continuous, 150A peak
- 208V 3-wire 50A continuous, 100A peak
- 120V/208V 4-wire 50A continuous, 100A peak

Inverter Components

The following describes typical components have been selected for a 15kW inverter design.

DC Bus Capacitors

DC Bus Worst-Case Voltage Ripple Calculation

Input Current	$I_{in} = 47$
Output Current	$I_{out} = 47 (1 + \sin 2\omega t)$
Ripple Current	$I_r = I_{out} - I_{in} = 47 \sin 2\omega t$
Ripple Voltage	$V_r = 47/ (2\omega C)$

For 50Hz operation, $\omega = 314.2$ rad/sec

For ripple voltage amplitude of less than 5V (10V peak-to-peak)

$$C \geq 14959 \ F$$

An electrolytic capacitor with a minimum rated voltage of 250V should be used. Each capacitor consists of 3 parallel-connected cans.

Capacitance	5600 F
Diameter	3.03"
Length	4.16"
Weight	1.19 lb
Suitable type	EPCOS B43456-A4568-M

Total 6 capacitors.

IGBT Modules

Rated voltage	600V
Rated current	200A (peak instantaneous)
Suitable type	BSM200GD60DLC
Configuration	Six-pack
Dimensions	4.78" x 2.43" x 0.81"

Weight	0.68 lb
Total 2 modules	

Operating conditions:

DC bus voltage	350V
Switching frequency	15kHz
Output current	25A rms
Case temperature	110°C
Junction temperature	115°C
Heatsink temperature	100°C
Loss per module	231W

Filter Inductors

The inductance value is chosen to limit the maximum peak-to-peak ripple in the filter circuit to 7A near the zero-crossing of the output waveform. This Figure corresponds to 10% of the peak-to-peak value of the full-load current fundamental.

Under these conditions the ripple current is given by:

$$Ir = Vdc/(4fL)$$

Where Vdc is the DC bus voltage and f is the switching frequency.

For Vdc = 350V, f = 15kHz and Ir < 7A

L > 833 H

The specification for the inductor is:

Minimum inductance (at zero current)	833 H
Continuous 60Hz current	25A rms
Peak 60Hz current	50A rms
Continuous 15kHz current	2.88A rms
Minimum inductance 71A DC	416 H

Target dimensions	4" x 4" x 4"
Target weight	4 lbs
Target for full-load loss	20W

Total six chokes

Output Filter Capacitors

These decouple the ripple current from the inductors by providing it with a low-impedance path to neutral. The peak-to-peak ripple voltage at the output terminal is given by:

$Vr = Ir / 8fC$

Where Ir = 7A, f = 15kHz

For Vr < 2V , C > 29.1 F
The capacitors must have a minimum DC voltage rating of 250V and a minimum AC voltage rating of 120V.
Suitable type is:
Six capacitors are required.

Dimensions	diameter 3" x length 3"
Weight	1.2 lb

Table 6 Overall weight, volume and loss summary

Item	Volume (cu in)	Weight (lb)	Loss (W)
DC Bus Capacitors	220	7.2	24
IGBTs	20	1.4	462
Heatsink	235	9.0	0
Filter inductors	384	24.0	120
Filter capacitors	162	7.2	12
Power connections	TBD	TBD	TBD
Control Circuits	100	2.0	30

Estimated total weight	50.8 lbs
Estimated total losses	648W
Estimated overall efficiency	95.68%

DC to DC Converter Output

It is possible to connect standard DC to DC converter modules designed for 360V DC input directly from the DC bus. These modules are typically available at up to 500W continuous rating (17.8A at 28V). Outputs of several modules may be connected in parallel. Other output voltages (eg 12V) are available.

Each DC to DC converter module:

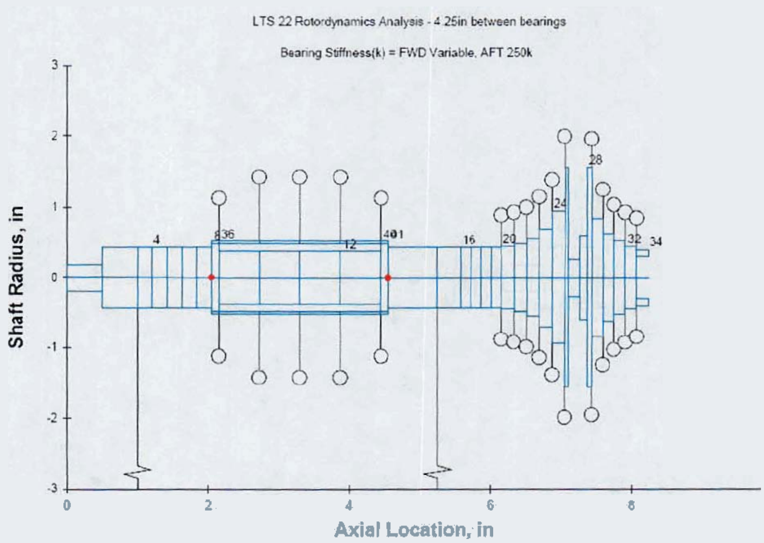
Input power	625W
Output Power	500W
Full-load losses	125W
Weight	1.0 lb
Dimensions	6" x 3" x 4"

The available AC output power is reduced if power is consumed from the DC output.

Rotor Dynamics

The LTS22 rotor system was designed so that the first critical bending mode occurred at a frequency well above the normal rotor operating speeds. To assure that this criteria was met, a Rotor Dynamics Analysis of the LTS22 engine configuration was performed to reflect the final selection of generator length, bearing placement and overall engine length. The final configuration was arrived at through iterative analyses during the design process which indicated the need for rotor length reduction and rotor diameter increase from an initial design concept. Analyses were performed using the XLrotor code at Locust to compute critical speeds. The model used in the final configuration analysis is shown in Figure 19.

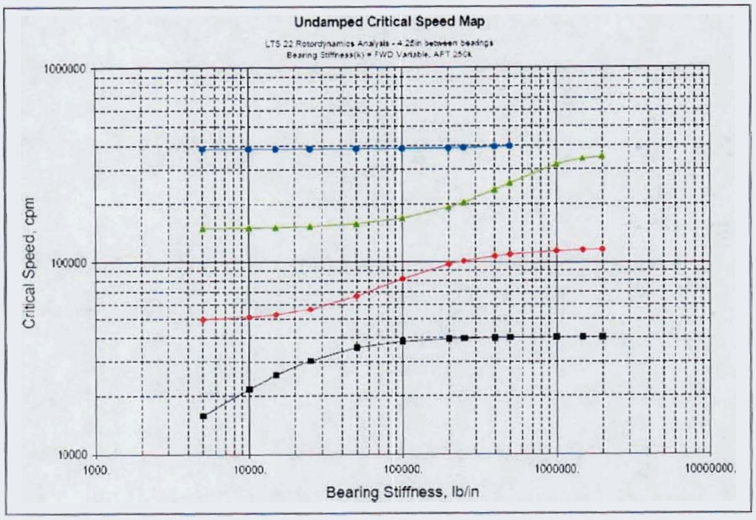
Figure 19 LTS22 Rotor System Model



The model includes the rotating parts of the rotor, shaft spacer and inner bearing races. These are represented by beam elements in the XLrotor code. Bearing supports are represented by springs. Gyroscopic stiffness and additional mass effects are also included.

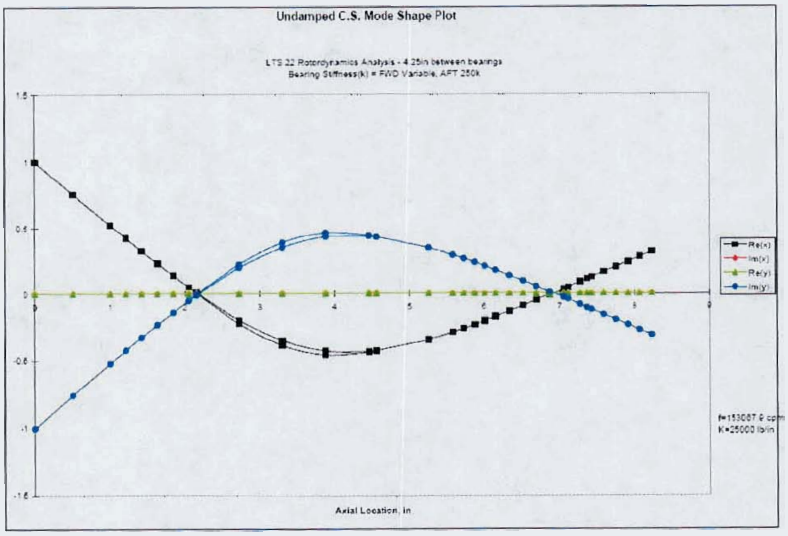
The analysis showed that the optimum bearing support stiffness for critical speeds was a combination of soft support for the forward bearing and hard support for the aft bearing. The predicted variation of critical speeds with forward bearing stiffness at the design aft bearing stiffness of 250K lb/in is shown in Figure 20. At a forward bearing support stiffness of 25K lb/in the first two critical speeds occur below 60K rpm.

Figure 20 LTS22 Critical Speed vs Front Bearing Stiffness



In order to obtain a relatively soft support of 25K lb/in, the forward bearing outer race is mounted on "O"rings. Because the first two critical speed modes are basically ridged body modes they are not likely to be amplified during transient engine start up. The first bending mode which is shown in Figure 21 occurs at 153K rpm which is safely above normal operating speed of 121,332 to 130,554 rpm.

Figure 21 LTS22 First Bending Mode



Bearings, Lubrication Systems and Thermal Management

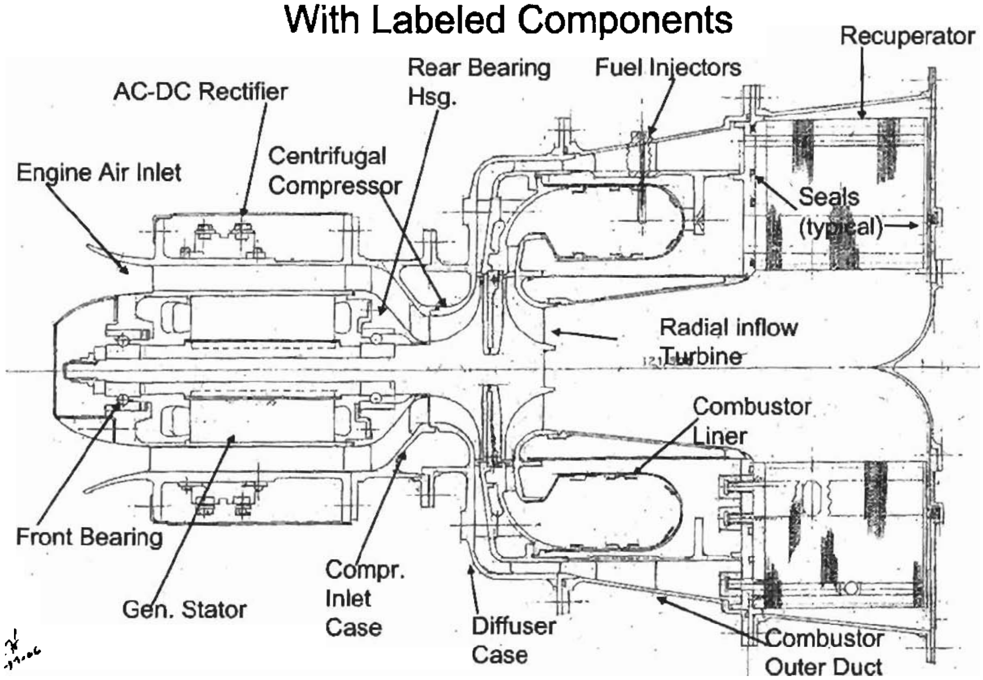
The LTS22 shaft is supported by a pair of ball bearings. These bearings employ Si3N4 ceramic balls and 440C stainless steel races for reduced wear and corrosion resistance. These bearings are projected to have a B10 life of greater than 5,000 hours. Two methods of lubrication are being considered, air/oil mist lubrication and dry film lubrication.

Mechanical Design

Rotor Construction

The LTS22 rotor is a one-piece cast and finish-machined nickel alloy part. On the aft end is the centrifugal compressor and radial in-flow turbine. The shaft projects from the impeller ID forward and provides mounting journals for the two angular contact bearings. The bearings are located on either side of the generator rotor and the compressor/turbine is overhung aft of the rear bearing. These components are shown in Figure 22 engine cross section. Shaft critical speed is a principal sizing parameter for the LTS22, and includes setting of the distance between bearings, the shaft diameter and the overhang from the rear bearing to the compressor/turbine CG. Refer to the Rotor Dynamics section of this report for additional details and discussion of critical speed issues. Because of the inherent simplicity of incorporating dry-lube bearings in the engine, the shaft can be made shorter due to fewer parts in the shaft axial stack-up. This greatly enhances the ability to position the critical speeds more favorably within the running range. Fewer parts results in a significant reduction of OEM and operational costs. The bearings are mounted in the engine back-to-back, with the two shoulders facing each other and a preload wave spring installed against the forward bearing's shoulder to provide a light preload.

Figure 22 LTS22 Cross Section
With Labeled Components



Engine Inlet and Generator Static Structure

The generator stator is shrink-fitted on the ID liner of the inlet duct. This duct consists of concentric inner and outer cylinders with an annular array of 36 fins which tie the structure together. The radial fins transfer heat from the stator windings, bearings and also from the OD mounted AC-DC rectifier. This waste heat is picked up by the inlet air and dissipated in the engine inlet. The inner section of the compressor inlet duct contains the rear bearing housing, just ahead of the impeller. The outer section of the inlet duct contains eight highly 3D struts that can be integrally cast with the inner section making it into a ring-strut-ring casing.

Diffuser/Combustor Static Structure

The diffuser case provides a portion of the engine structural backbone and is positioned between the compressor inlet case and the combustor outer duct (Figure 22). The transition case, containing the turbine nozzle vane ring,is bolted to the diffuser case radial wall.

Recuperator Structure

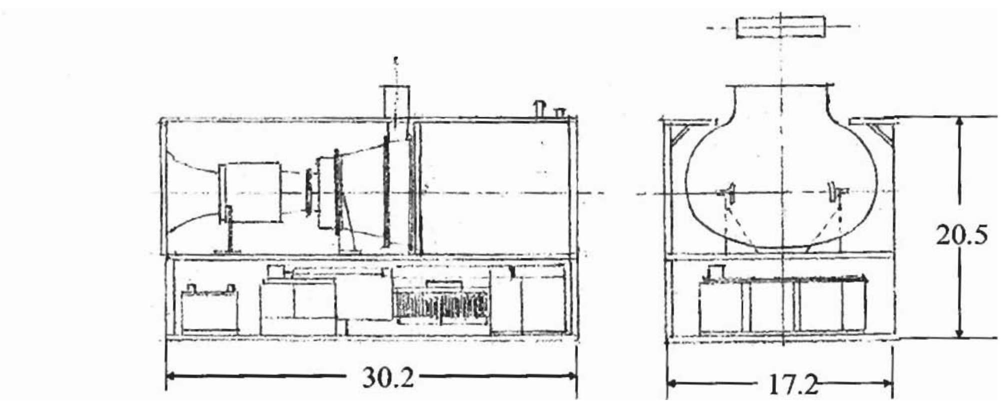
The recuperator section, mounts aft of the combustor and is bolted as an assembled unit to the rearmost outer duct flange of the engine, as shown in

Figure 22. Additional details of the heat transfer and performance characteristics of this unit are presented in the recuperator section of this report.

Housing Cabinet

All of the components and subsystems comprising the LTS22 turboelectric power generating system are packaged in a framed structure covered with removable panels (shown without panels in Figure 23). The power system components are arranged in two tiers inside the cabinet. The lower tier contains most of the electronic conversion/inverter elements, including cooling fans to carry away heat generated by these elements. The second tier contains the turbine engine with high speed generator, fuel tank and all the ancillary equipment necessary to operate the unit. An inlet air filter screen is shown at the forward end and is part of the cabinet. The vertical exhaust stack passes through the upper cabinet panel. The fuel tank with 6.5 gal. of volume is located at the rear of the second tier and provides enough fuel volume for 4 hours of operation at full power. The cabinet dimensions are: length 30.2 in, width 17.2 in, and height = 20.5 in. for a total volume of 6.16 ft^3. Dry weight of the LTS22 preliminary system package is estimated to be about 100 lbs. Weight to power ratio is 6.7 lb/KW and volume to power ratio is 0.45 ft^3/KW. These ratios are more than an order of magnitude better than current technology Army Diesel QTG generators.

Figure 23 LTS22 Generator System Cabinet



Dimensions in inches

Recommendation

The preliminary design of the LTS22 15 KW small turboelectric power generator system shows that a very compact, light weight generator can be designed using advanced technologies that include: a CLF recuperated microturbine engine that operates on heavy fuel, an integral high speed generator and an electronic power converter. The resulting LTS22 generator design has weight to power and volume to power ratios that are more than an order of magnitude better than current technology Army diesel QTG generators. Because of these very large potential advantages, the LTS22 should be continued through detail design, fabrication, and system demonstration testing.

Publications and Technical Reports

There were no publications or technical reports under this contact.

Participating Scientific Personnel

Name	Specialty
• Daniel C. Mikkelson	R&D Project Manager
• Brain A. Robideau	Compressor
• Robert R. Sellers	Turbine
• Robert M. Pierce	Combustor & Recuperator
• James R. Hendershot	High Speed Starter/Generator
• Dr. Tony Davis	Electronic Converters
• James Hurchalla	Rotor Dynamics
• H. Lawrance Hess, Jr.	Bearings/Lube Systems/Thermal Management
• Edward C. Hill	Mechanical Design